Away-side asymmetry of jet correlation relative to reaction plane: a sensitive probe for jet in-medium modifications

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We proposed a new observable based on two particle azimuth correlation to study the away-side medium response in mid-central Au+Au collisions. We argue that a left/right asymmetry may appear at the away-side by selecting triggers separately in the left and right side of the reaction plane. A simple model estimation suggests that the magnitude of such asymmetry could reach 30% with details depends on the medium response mechanisms. This asymmetry, if observed, can help to distinguish competing theoretical models.

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Recent results from Relativistic Heavy ion Collider (RHIC) indicate the creation of a new state of matter in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. This matter behaves like a fluid of strongly interacting quarks and gluons as indicated by its strong collective flow, low kinetic shear viscosity and large opacity [1]. It is commonly referred to as the strongly coupled quark-gluon plasma (sQGP). Current efforts are focused on the detailed characterization of the properties of the sQGP.

Energetic jet and back-to-back dijet pairs have been used extensively to probe the properties of the matter. The interactions between jet and medium not only lead to a strong suppression of single hadron yield and away-side dihadron pair yield in central Au+Au collision at high p_T [2, 3], known as jet-quenching; it also results in characteristic responses of the medium to the energy deposited by the quenched jets [4, 5]. Such medium responses appear as several interesting features in the two particle azimuthal angle correlation at low p_T, including the near-side elongation in pseudo-rapidity (the ridge) and the away-side double-shouldered structure at $\pi \pm 1.1$ [5, 6, 7]. The latter have been interpreted as the possible excitation of conical flow [8, 9], however the exact physics origins are currently under intense debate [10].

Our understandings of jet quenching and medium response are based primarily on how the single particle yield and dihadron correlation vary with the collision geometry, such as event centrality, system size and more recently the angle with respect to the reaction plane (RP). Most theoretical models can describe the centrality and system size dependence of the single particle and dihadron data [11, 12]. However they do not do a good job in describing the RP dependence. The observed anisotropy for single particle suppression at high p_T seems to be incompatible with energy loss models [13]. The dihadron correlation also shows a characteristic dependence of the medium response on the angle with respect to the RP that currently lacks theoretical descriptions [14, 15]. On the experimental side, the physics signals (survived jets and medium responses) in the previous RP dependence studies are more susceptible to the influence of hydrodynamic flow than inclusive studies. This is because the flow modulation is bigger in RP dependent correlation ($\propto v_{2n}$) than that for the inclusive correlation ($\propto v_{2n}^2$) [16]. In this letter, we propose a new observable that is sensitive to the medium response mechanisms, and can offer some insights on the decomposition between jet and hydrodynamic flow.

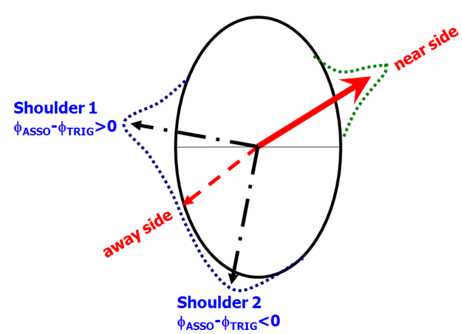

FIG. 1: (Color Online) Schematic view of the path length difference for the two shoulders associated with away-side when trigger is selected at an angle relative to the reaction plane (indicated by the horizontal line).

Our idea is illustrated in Fig. 1. A dijet pair is created and propagated through the medium. One jet exits the medium and fragments into hadrons containing the trigger; while the away-side jet loses energy and turns into two branches of medium responses at angle $\pi \pm 1.1$ relative to the trigger. These two branches have different path length in the medium, and this difference reaches maximum when trigger angle ϕ_s is selected at $\phi_s \approx \pm\pi/4$. If the magnitude of medium response depends on the path length, one expects to see a left right asymmetry. In the case of conical flow, the medium responses propagate and attenuate in the medium due to

finite viscosity. This may lead to more observed signal at the side with shorter path length. On the other hand, if the medium response increases with the path length, then one expects the opposite trend. This can happen if the medium is pushed outward by the shower gluons which may be dominantly radiated at large angles relative to the original hard-scattered partons [17]. Thus the observation of asymmetry may help us to distinguish competing medium response mechanisms.

But can this asymmetry be observed experimentally? Most RHIC experiments determines the RP orientation using the second order event plane which usually has the best resolution. This plane has a periodicity of π, which means it does not distinguish two dijet pairs that are connected by a rotation of π, $\phi_s \to \phi_s - \pi$ (Fig.2a). It can, however, distinguish the two pairs that are connected by a change in the sign, $\phi_s \to -\phi_s$ (Fig.2b) [18]. Previous studies did not see such left right asymmetry with second order event plane [14, 15, 19], because they fold the trigger angle bins into 0-$\pi/2$ range, which automatically averages out the asymmetry.

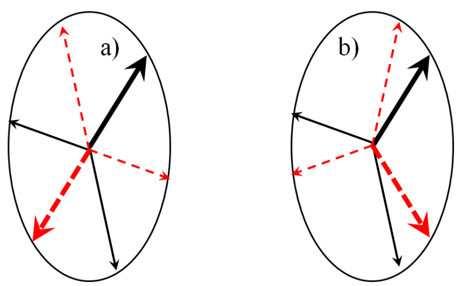

FIG. 2: (Color Online) Two dijets (solid and dashed) that are connected by a) a rotation of $\phi_s \to \phi_s - \pi$ and b) a change of the sign $\phi_s \to -\phi_s$. The thick and thin lines indicates the survived near-side jet and medium responses to quenched away-side jet, respectively.

Our arguments for left right asymmetry is valid on general grounds, however a quantitative estimation needs to take into account the energy deposition, generation and propagation of medium response in a realistic geometry. Fig.3 shows a more realistic scenario, in which the away-side jet is created at point A and is quenched after traveling to point B. The medium response can be generated anywhere in between A and B, and propagates along the two shoulder directions. Due to surface bias of triggered correlation analysis, point B usually lies deeper into the medium than point A. For a given medium response mechanism, the magnitude of the left/right asymmetry is mainly controlled by collision geometry, i.e. the probability distribution of the hard-scattering point A and density distribution of the medium. The asymmetry is also sensitive to the k_T broadening, because it leads to a swing of away-side jet in azimuthal angle relative to the trigger, which changes the path length for the medium response.

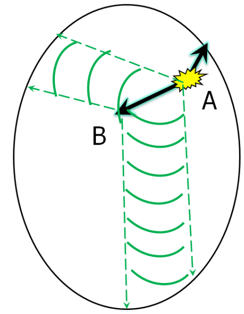

FIG. 3: (Color Online) A more realistic view of the dijet and associated medium responses.

We estimate the magnitude of the asymmetry using a simple jet absorption picture based on the Glauber model [12]. In this picture, dijets are generated according to binary collision density profile in transverse plane with uniform orientation and a k_T smearing of 0.4 radian according to the $p+p$ data [20]. These dijets then traverse the medium whose density is given by participant density profile. Woods-Saxon nuclear geometry is used in generating both the collision and the participant density profiles. For each generated jet at (x,y) (point A) propagating along direction (n_x, n_y), we calculate the quenching point B according to survival probability $e^{-\kappa I}$, where the matter integral I is

$$\begin{aligned} I &= \int_0^\infty dl\, l \frac{c\tau}{l+c\tau} \rho(x+(l+c\tau)\,n_x, y+(l+c\tau)\,n_y) \\ &\approx c\tau \int_0^\infty dl\ \rho \end{aligned} \tag{1}$$

which corresponds to a quadratic dependence of absorption ($\propto\ ldl$) in a longitudinal expanding medium ($\propto c\tau/(c\tau+l)$) with a formation time of $\tau = 0.2fm/c$. κ is fixed at 0.7 to reproduce the centrality dependence of R_{AA} [12]. We select those dijets where one jet survives and fragments to the trigger particle and the companion jet is quenched, leading to the associated particles. The probability for such dijet is

$$f \propto e^{-\kappa I_{jet_1}} \left(1 - e^{-\kappa I_{jet_2}}\right) + e^{-\kappa I_{jet_2}} \left(1 - e^{-\kappa I_{jet_1}}\right). \tag{2}$$

The spread of the fragmentation of the survived jet is chosen to be 0.3 radian which essentially fixes the near-side width. If jet is found quenched, the associated medium responses are generated uniformly between point A and point B at angle $\pi \pm 1.1$ relative to the trigger with an initial azimuth spread of 0.3 radian. To enable the left/right asymmetry, we assume the medium response is attenuated according to Eq. 1. This leads to an average attenuation of $\left\langle e^{-\kappa c\tau \int_0^\infty dl\ \rho} \right\rangle \approx e^{-1.3}$ for 30-35% centrality Au+Au collision. As pointed out in [9], a small viscosity of only a few times the universal lower bound [21] can lead to such level of attenuation.

Fig 4a shows the calculated away-side distribution for trigger hadrons in 30-35% Au+Au centrality. To maximize the asymmetry, the angle of the triggers are selected at around $\phi_s = \pm\pi/4$ relative to the RP. The overall shape of the away-side and its angular dependence patten is controlled by the geometry. The multiplicities for the near-side and away-side are chosen such that the observed amplitudes (average over left and right) mimic the experimental data. Two features can be clearly seen. One is the suppression of one shoulder peak relative to the other, as a result of the path length dependent attenuation of medium response. The second feature is a small shift of shoulder peak positions and broadening of their widths, as a result of the away-side k_T smearing. The overall observed asymmetry is on the order of 30%. Fig 4b shows the case where the finite RP resolution is taken into account. The observed asymmetry is rather sensitive to the accuracy with which one can measure the RP. A typical resolution of 0.8 used by RHIC experiments reduces the observed asymmetry by about 50%.

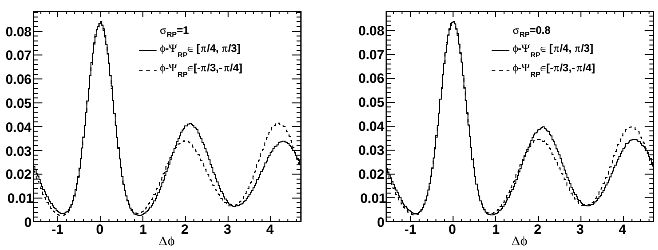

FIG. 4: The dihadron correlation for triggers angle ϕ selected at around $\pm\pi/4$ relative to the reaction plane. a) is for ideal case and b) is for the case where the reaction plane resolution is 0.8.

In non-central Au+Au collision, medium response always coexists with hydrodynamic flow, which makes the clean separation of the two effects challenging. The common experimental approach is to assume that the correlation function consists of a jet-induced signal and a pure flow term, and to further assume the jet signal is zero at its minimum $\Delta\phi_{min}$. Recently, this Zero Yield At Minimum or ZYAM approach [5] has been extended to RP dependence correlation analysis [14, 15, 19]. For triggers selected at a fixed angle ϕ_s with ideal RP resolution, the correlation function defined in [7] takes the following form [16]:

$$C(\Delta\phi) = \mathrm{Jet}(\Delta\phi) + \xi(1 + 2v_2^{\mathrm{assoc}} \cos 2(\phi_s + \Delta\phi)) \quad (3)$$

v_2^{assoc} is the elliptic flow for associated hadrons, and ξ is the pedestal level in same event measured relative to mixed event, i.e. $\xi = \langle n_{\mathrm{trig}} n_{\mathrm{assoc}}\rangle / \langle n_{\mathrm{trig}}\rangle\langle n_{\mathrm{assoc}}\rangle$, where n_{trig} and n_{assoc} denote the multiplicity of triggers and partners, respectively [7]. ξ is typically very close to one in central and mid-central Au+Au collisions [7], so we simply fix it to unity.

Equation 3 indicates that the selection of trigger in a fixed angle ϕ_s leads to a phase shift of $2\phi_s$ in the flow term. Fig. 5 illustrates the influence of possible residual flow left over after flow background subtraction for triggers selected at $\phi_s = \pm\pi/4$. The input jet shape and magnitude (thin line in left panel) is adjusted to the experimentally measured jet signal (jet pair fraction) for $3-4\times1-2$ GeV/c bin in 30-40% Au+Au collisions [7]; the residual flow is assumed to be the size of the v_2 systematic uncertainty, i.e. 5% of the measured v_2^{assoc}. Fig. 5 clearly shows that residual flow can lead to a significant away-side asymmetry at 40-50% level. This magnitude of the asymmetry is larger than the real asymmetry shown in the left panel of Fig. 4. However, it is possible that the actual residual flow is smaller [22]. Furthermore, residual flow also leads to a comparable left/right asymmetry at the ZYAM minimum (around ±1 radian), while real medium response of Fig. 4 does not show such asymmetry at ZYAM minimum. So by comparing the RP dependent correlation for trigger selected at ϕ_s and $-\phi_s$, one may be able to detect and constrain possible residual flow. Such residual flow can be caused by uncertainties in flow measurements, but it may also indicate that triggered events have intrinsically different flow from the inclusive events, possibly due to couplings between jets and medium.

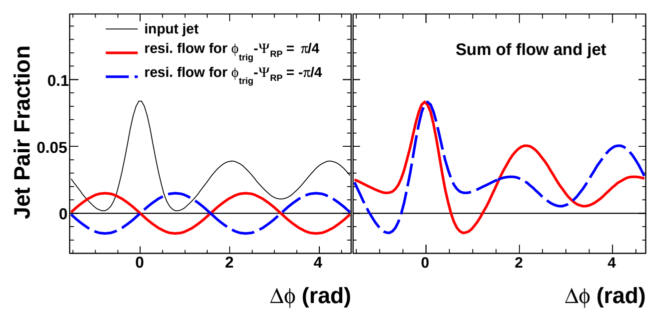

FIG. 5: (Color Online) Illustrating the effects of the residual flow (assuming to be 5% of the experimental measured mean value) on the left and right asymmetry. The input jet shape and amplitude (thin line in left panel) is adjusted to mimick the experimentally measured jet signal (fraction of jet pair over all pairs) for $3-4\times1-2$ GeV/c selection from 30-40% Au+Au collisions [7].

Following the same arguments, it is possible that the near-side medium response (the ridge) also has left/right asymmetry, caused by the path length difference between partons emitted at the left side and those emitted at the right side of the trigger. However, since the near-side width is quite narrow, the effect due to path length alone may be too small to be detectable. We leave this for a future study.

In summary, we propose to study the jet correlation by selecting triggers separately in the left and right side of the second harmonic event plane. The correlation signals for triggers selected this way are sensitive to the

left right asymmetry of the geometry associated with the away-side jet. This asymmetric geometry is expected to lead to asymmetries for away-side jet shape. Experimental studies of the shape and magnitude of this asymmetry may shed light on the underlying medium response mechanisms. Such studies may also help us to understand possible influences on the v_2 measurements by the coupling between the jets and the flowing medium. (Indeed both PHENIX and STAR has seen indications of such asymmetry at the recent Quark Matter conference [23].)

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